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GENERAL CHARACTERISTICS OF HEAVY ION PLASMA CREATED BY LASER

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16. Abstract

A synthesis of the principal results obtained during the interaction of laser radiation with matter, and particularly the results concerning the charge state, the energy, and energy distribution of ions emitted by the plasma, is presented. From these results the utilization of these plasmas as a source of heavy multicharged ions is envisaged and the characteristics of the desirable laser are defined in this case.

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G. Tonon

I. INTRODUCTION

The principal difficulty encountered in the development of a heavy-ion accelerator resides in the low charge state of these ions as they leave the sources which are currently operational. Consequently in recent years there has been a notable increase in research toward developing new sources[1-11], and of these projects a certain number have been based on the use of equipment developed in the area of controlled fusion research[5-11]. This is explained by the fact that the conditions necessary for the production of ions carrying Z charges are much less rigorous than those required by controlled fusion. In the case of a multiple ionization we have: /2

$$\begin{aligned} &10 < Z < 50 \\ &10^{10} < n_e\tau < 10^{13} \quad \frac{es}{cm^3} \\ &50 < T_e < 2000 \text{ eV.} \end{aligned} \tag{1}$$

Ordinary equipment operating in densities between 10^{10} and 10^{12} e/cm^3 should therefore achieve a confinement period of more than one second, which appears to be difficult to produce. On the other hand, laser-created plasma with a very high density (10^{21} e/cm^3 when a neodymium glass laser is used) needs a life of $\tau \sim 10^{-9}$ s, which is generally produced by the inertial confinement peculiar to this type of plasma. It is therefore possible to produce ions with a high charge state within a laser plasma, but this does not suffice as a source of ions which can be used at the level of an accelerator. More specific characteristics therefore

intervene, such as the current released, the geometry of the bundle and the usable length of the cycle, all of which are characteristic of laser plasma, as we are about to show.

II. LASER/MATTER INTERACTION: PRODUCTION OF HIGHLY-CHARGED IONS /3

II.1. Interaction Between Radiation and Matter

Two models have been proposed to interpret the interaction of laser radiation with matter:

a) The "self-regulated" model[15,16], in which the hydrodynamic equations are solved by assuming that the plasma develops in such a way that, constantly:

$$K X_o = \text{constant}$$

K = absorption coefficient[12,13]

X_o = plasma size

b) The "radiative deflagration" model[17], in which one assumes that absorption is achieved in a very thin slice of matter whose density is equal to the density of section n_{ec} of the beam.

$$\left[\left(n_{ec} = \frac{10^{21}}{\lambda^2_{\mu m}}\right)_{e/cm^3}\right.$$ where λ is the wavelength of the laser.]

In the area of laser flux Φ which has been the object of the majority of the experiments ($10^9 < \Phi < 10^{13}$ W/cm^2), both models result in fairly similar values for the plasma characteristics. For example, the density and temperature profiles for radiative deflagration are schematically shown in Figure 1. The impact of the laser beam (which is then absorbed by the density of section n_{ec}) on the solid surface in the vacuum produces a transfer of

energy and momentum from light to matter. The matter is heated and set in motion.

A standing wave will flow in the direction of the vacuum. But /4
since the substance has come under high pressure, compression waves and shock waves may also be produced. The atoms of the cool, inactive medium therefore are first reached by an impact (Figure 1 c) which heats them and sets them in motion inwardly. But a relaxation front overtakes them and they are then accelerated in the opposite direction and heated and therefore ionized in the conduction zone. For this model the plasma temperature is given as:

$$T_{(eV)} = 1{,}25.10^{-6} \left(\frac{A}{Z}\right)^{1/3} \left(\lambda^2 \Phi_{(W/cm^2)}\right)^{2/3} \qquad (2)$$

where λ is given in microns,

and the flow of matter ejected from the vacuum per unit of irradiated surface:

$$\frac{dN}{dt} = \frac{10^{24}}{A^{1/3} Z^{2/3}} \left[\frac{\Phi_{(W/cm^2)}}{\lambda^4}\right]^{1/3} \quad ions.cm^{-2} \qquad (3)$$

Numerous measurements of the electronic temperature of the plasma have been made experimentally[18-25] and the results are summarized in Figure 2, where, taking (7) into account, the development of $T_e \times \left(\frac{Z}{A}\right)^{1/3}$ as a function of $\lambda^2 \Phi$ is outlined. We note on the one hand that for $\lambda\Phi \sim 10^{13}$ W/cm^2 the electronic temperature of the plasma is close to keV and on the other hand that the results are relatively close to the theoretical projections.

By contrast the flow of matter during the laser pulse has been little studied. Figure 3 shows the development of the total num-

ber of electrons ejected N_e measured by interferometer[26]; in this experiment a polyethylene target was irradiated using a neodymium-doped glass laser. Using these methods and an ionization model which will be discussed in the following paragraph, it is possible to find the total number of ions emitted N_i. Thus at the end of 20 ns, 10^{16} ions are produced.

II.2. Initial Charge State of the Ions

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The formation of multi-charged ions obviously depends on the density and electronic temperature of the heated medium, which as we have seen can be very high. According to Stratton[27], for:

$$n_e \left(\frac{e}{cm^3}\right) < 3.10^{13} \chi_Z^3 (eV) \, T_e^{1/2} (eV) \qquad (4)$$

χ_Z = ionization potential corresponding to charge state Z.

a condition which in practice is always fulfilled for plasma created by laser, a "solar corona" type ionization model should be considered. In this case for an ion Y we have the process:

- for ionization by collision $e + Y^Z \rightarrow Y^{Z+1} + e + e$
- for radiative recombination $Y^{Z+1} + e \rightarrow Y^Z = h\nu$.

So that ions having a charge state Z are produced in the plasma, the heating period τ_c must be at least as long as the ionization period τ_Z, which can be very accurately determined by only considering the last ionization[28]:

$$\frac{1}{n_e \tau_Z} = S_Z^{Z+1}(T_e) + \alpha_{Z+1}^{Z}(T_e) \qquad (5)$$

where $S_Z^{Z+1}(T_e)$ and $\alpha_{Z+1}^{Z}(T_e)$ are respectively the coefficients

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of ionization and recombination determined, for example, by McWhirter[29]. The heating period is equal to the time it takes an ion to pass through the heated zone of the plasma, whose size is determined by the electronic conduction, that is[12]:

$$n_e \tau_c = 10^8 \left(\frac{A}{Z^2}\right) T_e^{3/2}\ (eV) \quad \left(\frac{es}{cm^3}\right) \qquad (6)$$

Outlined in Figure 5 is the development of $n_e \tau_Z$ and $n_e \tau_c$ as a function of the electronic temperature of the plasma, for carbon and iron ions. Taking into account equation (2) linking T_e to the laser flux ϕ we can thus compare the experimental results obtained by spectroscopy (which accurately furnish the charge state of the ions at target level) with the computed results (Table 1).

Table 1

$\lambda_{\mu m}$	$\lambda^2 \phi$ (W/cm²)	Nature of Target	Z Factor Observed	χ_i	Computed Z Factor	Réf.
$\lambda = 0{,}6943$	$1{,}5.10^{11}$	Polyethylene	6	475	6	/19/
$\lambda = 0{,}6943$	3.10^{11}	Iron	16	506	16	/30/
$\lambda = 1{,}06$	2.10^{10}	calcium	12	641	7	/31/
	2.10^{11}	"	13	724	11	/31/
	5.10^{12}	calcium	15	808 471	18	/31/
	$\sim 10^{12}$	aluminium calcium	11 14	895	11 14	/32/

Generally, therefore, there is excellent agreement between /7
theory and experiment.

The interaction of the laser beam with matter produces ions with a high charge state. We will now discuss the behavior of these ions as they expand in the vacuum.

III. CHARACTERISTICS OF IONIC EMISSION OF PLASMA CREATED BY LASER /8

In order to use ions created by laser in a source, it is important to determine three characteristics:

1) Charge state Z_∞ of the ions after expansion in relation to their initial charge state Z_o, discussed in the preceding.

2) Kinetic energy of the ions or, better still, their energy spectrum.

3) Directivity of emission.

III.1. Freeze of Distribution Function ($Z_\infty \simeq Z$)

When a laser-produced plasma is used as a source of ions, some ion expansion is inevitable and because of this fact the recombination processes may considerably reduce the initial charge state Z_o of the ions. In fact, as we are about to show, the structure of the plasma is such that an actual freeze of ionic distribution results.

Spectroscopy[19] reveals that this expansion is adiabatic and that the relationship between density and electronic temperature at each point in the plasma is:

$$T_e \, n_e^{-2/3} = C^{te}$$

Since the characteristic recombination time τ_Z, according to (5), equals:

$$\tau_Z = \frac{1}{n_e \alpha_Z} \qquad (8)$$

with footnote 29:

$$\alpha_Z = B\, T_e^{-1/2} \qquad \text{or} \qquad B = f(Z, \chi_Z) \qquad (9)$$

the result is: /9

$$\tau_Z = \frac{1}{B} \frac{T_e^{1/2}}{n_e}$$

According to equation (7), $\tau_Z \to \infty$ when $n_e \to 0$. The density profiles, schematically shown in Figure 1, show high density gradients[33,34]. The result is that in the zone of expansion the characteristic recombination time τ_Z becomes very long, and because of this fact the initial charge state of the ions will be conserved to a large degree ($Z_\infty = Z_o$).

This has been verified by a number of measurements[35-40] taken several dozen centimeters from the target by means of particle analyzers. Results of these measurements are assembled in Figure 6. This diagram traces the development of the measured charge state Z (represented here by the corresponding ionization potential χ_Z) as a function of $\lambda^2\Phi$, and it also gives in detail the computation results which indicate the initial charge state Z_o. The excellent agreement between measurements and computation shows that in practice the charge state of the ions is conserved as they expand in the vacuum. In this figure the first results obtained with a CO_2 laser should also be noted ($\lambda = 10.6\ \mu$ - $\lambda^2\Phi = 10^{11}$ W/cm^2); these led to the occurrence of A_e^{9+} and F_e^{14+} ions[40].

III.2. Kinetic Energy of the Ions

Finding the expression for the average kinetic energy $\langle W \rangle$ of the ions becomes an easy matter when one realizes that almost all laser energy is in the form of directed energy. Thus:

$$\langle W \rangle = \frac{\Phi \tau S}{N_i} \tag{11}$$

where τ is the duration of the laser pulse which is focused on a surface S, and N_i is the total number of ions emitted defined by equation (8). With all computations made the result is: /10

$$\frac{\langle W \rangle}{A} = 4{,}7.10^{-9} (\lambda^2 \Phi)^{2/3} \times \left(\frac{Z}{A}\right)^{2/3} \left| \text{ in } \frac{\text{keV}}{\text{Nucleon}} \right. \tag{12}$$

This average energy has generally been measured by means of charge collectors[40-44] and Figure 7 shows the results as a function of the incident laser flux (the ion charge Z was deduced from the experimental results discussed in the preceding paragraph). The agreement between theory and experiment seems to be quite satisfactory, and we should note the occurrence of iron ions having an average energy of 20 keV when the laser flux is equal to 2.10^{12} W/cm^2.

III.3. Directivity of Emission

Because of the same laser-matter interaction the ions acquire a velocity which is preferentially perpendicular to the surface of the target. As J. Dawson et al. have shown[45], aside from hydrodynamic considerations, the plasma first expands in the direction of its smallest dimension, which as we have shown is limited by the zone of absorption of the laser beam.

Cinematographically, a stream of matter is clearly detectable which is more directed the stronger the luminous flux[46]. This has also been confirmed by a number of measurements taken by means of a charge collector[36,47,48,49,38].

An analysis of the angular distribution of each type of ion has been made spectroscopically[50] and by means of a particle analyzer[37]. The ions having the highest charge are found preferably in the vicinity of the normal to the target; thus there is a virtual spatial separation of various charge states.

IV. USE OF PLASMA CREATED BY LASER AS A SOURCE OF MULTI-CHARGED IONS /11

It appears that the "ideal" source for heavy ions, according to the requirements of nuclear physics, should satisfy the following characteristics[51,52,53]:

1. Nature of the ions arbitrary as long as $\varepsilon = \frac{Z}{A} \sim 0.2$.
2. Flow of at least 10^{11} pps associated with a useful cycle greater than 10%.
3. Emission of between 100 and 500 mm-mrad.
4. Length of life of at least several hours.

In the following we will try to define the conditions which a source of ions created by laser should fulfill in order to satisfy these stipulations, keeping in mind that all types of ions can be generated by the laser bundle.

1. Charge state.

Taking the Figure 6 results into account it would appear that:

a) For $3.10^{11} < \lambda^2\Phi < 2.10^{12}$ W/cm^2 the condition $\varepsilon \sim 0.2$ is satisfied for all bodies with a mass less than 100.

b) For $\lambda^2\Phi \simeq 2.10^{13}$ W/cm^2, $\varepsilon \sim 0.2$ is obtained even if uranium is used. It should be noted, however, that when $\lambda^2\Phi$ is close to 10^{13} W/cm^2, a large reflectance of the laser beam by the plasma is observed[54], which the theoretical model does not take into account. This reflectance reaches 50% of the incident flux /12
and because of this fact the calculated flux values should actually be increased at least by a factor of two.

2. Flow from the source.

With a frequency of laser pulse ν the ion source should:

a) Emit during a time period $\Delta\tau$ so as not to exceed the maximum current I_o tolerated by an accelerator. According to M. Reiser and V. Viola[55], the number of corresponding ions N_o is given by:

$$N_o = 6{,}25.10^{18}\, I_o\, \frac{\nu.\Delta\tau.\delta}{z} \geqslant 10^{11} \text{ pps.} \qquad (13)$$

where δ is the micro-duty factor. Taking as typical values I_o = 50 mA and δ = 0.1, the final result is:

$$\Delta\tau \geqslant 3{,}2.10^{-6}\, \frac{z}{\nu} \qquad (14)$$

b) Contain the number of charge Z ions desired. According to equation (3) the laser will initially generate:

$$N_T = 10^{24} \left(\frac{\lambda^2 \Phi}{\lambda^2}\right)^{1/3} \cdot \frac{S \cdot \tau}{\varepsilon^{2/3} A} \cdot \nu \quad \text{(pps)} \qquad (15)$$

where S (in cm^2) is the area of impact of the bundle and τ the length of the laser pulse. However during their initial expansion part of these ions will recombine and the number of usable charge Z ions is actually given by:

$$N^Z = \eta(Z) \cdot N_T \qquad (16)$$

where $\eta(Z)$ is a factor which can be deduced from the experimental results. Thus according to (15) and (16) 10^{11} pps are produced if: /13

$$\nu \geq 10^{-13} \times \frac{\varepsilon^{2/3} A}{\eta(Z) (\lambda^2 \Phi)^{1/3}} \times \frac{\lambda^2}{S \tau} \qquad (17)$$

c) Effectively furnish the current I_o desired, taking into account the space charge, which will limit extraction. This extraction, which occurs during the expansion of the plasma[56,57] is schematically shown in Figure 8. Since the plasma is very dense and hot, the extraction occurs at its periphery, which shifts at a speed v. The amount of current extracted is thus determined by the Child-Langmuir law[58] and is in this case:

$$I_{(A)} = 5{,}45.10^{-8} \cdot \frac{\pi . R^2}{D^2} \cdot \frac{\varepsilon^{1/2} V^{3/2}}{\left(1 - \frac{v}{D} t\right)^2} \qquad (18)$$

V = extraction voltage

The function of the expansion chamber is to diaphragm the plasma and to prevent all but the most highly charged ions from reaching the extraction area. As we have seen these ions are preferably emitted normal to the target. Moreover since the most highly charged ions are also the fastest and are thus found at the

edge of the plasma, they will tend to be the ones extracted.

3. Laser characteristics.

Table 2 summarizes the characteristics of the ion source and the characteristics the laser should possess.

TABLE 2

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		Iron	Molybdenum	Uranium	
	A	56	96	238	238
	ε	0,28	0,2	0,1	0,2
	Z	16	20	25	50
	$\lambda^2 \Phi$ (W/cm^2)	3.10^{11}	10^{12}	10^{12}	2.10^{13}
	η (Z)	10^{-3}	10^{-4}	5.10^{-5} (extrapolation)	10^{-6}
Neodymium Laser $\lambda = 1,06\,\mu$ $S = 10^{-4}$ cm^2 $\tau \sim 3.10^{-8}$ s	N_T / ν	10^{15}	$8,7.10^{14}$	5.10^{14}	10^{15}
	N^2 / ν	10^{12}	$8,7.10^{10}$	$2,5\ 10^{10}$	10^{9}
	ν	0,1	1	4	100
	$\Delta\tau$ (Δ)	5.10^{-4}	$6,5.10^{-5}$	2.10^{-5}	$1,6.10^{-6}$
CO_2 Laser $\lambda = 106\,\mu$ $S = 3,10^{-4}$ cm^2 $\tau \sim 10^{-7}$ s	N_T / ν	10^{14}	$8,7.10^{13}$	5.10^{13}	10^{14}
	N_2 / ν	10^{11}	$8,7.10^{9}$	$2,5.10^{9}$	10^{8}
	ν	1	10	4.10	10^{3}
	$\Delta\tau$	5.10^{-5}	$6,4.10^{-6}$	2.10^{-6}	$1,6.10^{-7}$

It should be pointed out:

1. That the duration of emission should generally be much greater than the duration of the laser pulse and that it is between approximately 10^{-6} and 10^{-5} sec. This can be achieved by means of a basal activation period of appropriate duration.

2. The frequency ν of the laser is proportionate to λ^2 and thus is 100 times greater for the CO_2 laser than for the glass laser. Its maximum value should be on the order of kHZ. /15

The desired characteristics should be compared with the characteristics of existing lasers, which are assembled in Table 3.

TABLE 3

λ μm	Energy (joules)	τ	P (watts)	divergence (rad)	(W/cm^2)	Réf.
1,06	46 à 90	12 à 25ns	4.10^9	4.10^{-5}	10^{15}	/59/
	100	10 ns	10^{10}	5.10^{-5}	10^{15} à 10^{16}	/60/
	250	5 ns	5.10^{10}	10^{-4}	10^{15}	/61/
10.6	0,5 - 1	250 ns	$\simeq 10^6$	$< 10^{-3}$	5.10^{11}	/62/
	9	1 μs	$1,2.10^7$	Not specified	$\sim 10^{12}$	/63/
	30	1 μs	5.10^7	2.10^{-3}	$\sim 5.10^{12}$	/64/
	130	2 μs	5.10^7 à 10^8	Not specified	$\sim 5.10^{12}$	/65/

If the glass laser produces and does so in excess of the fluxes required, its rate of repetition will be very small and in practice it will not exceed one activation every five minutes.

On the other hand the fluxes obtained with the CO_2 laser are not yet adequate, at least for U^{50+}; however the rhythm of operation can be very fast, on the order of kHZ[64,66], with a peak power which for the moment does not exceed $2.5 \cdot 10^7$ watts[67]. As a result, the realization of a CO_2 laser capable of performing as a source of F_e^{16+} ions producing 10^{11} pps seems to be a practical possibility.

V. CONCLUSIONS

From theoretical and experimental research on the interaction of the laser beam with matter comes the fact that ions with a very high charge state (CO^{24+}, F_e^{22+}) have been detected and analyzed. Furthermore the very distinct directivity of emission, in energy as well as charge, facilitates the future extraction of these ions and guarantees the geometric quality of the ion bundle.

It follows that for ions with a mass $A \leq 100$ the realization by laser of a source of heavy ions fulfilling the requirements of nuclear physics ($\varepsilon \simeq 0.2 - 10^{11}$ pps) can be considered a practical possibility, if a CO_2 laser with transverse discharge operating at a rate of about 100 H^z is used.

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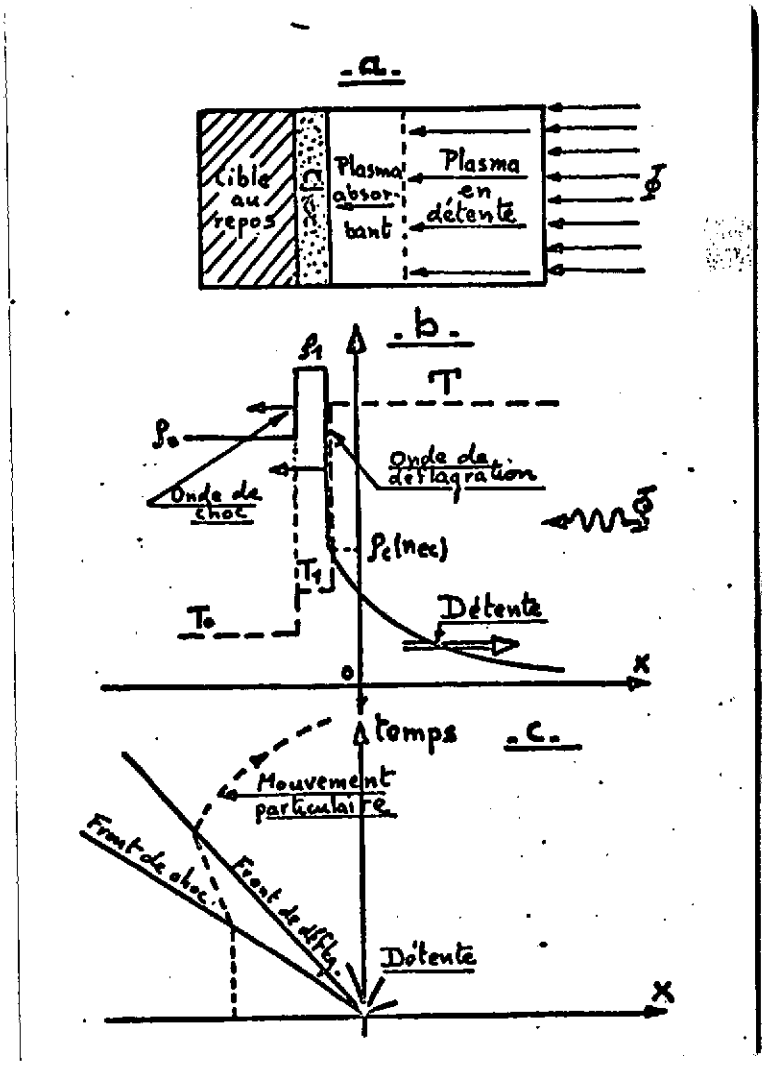
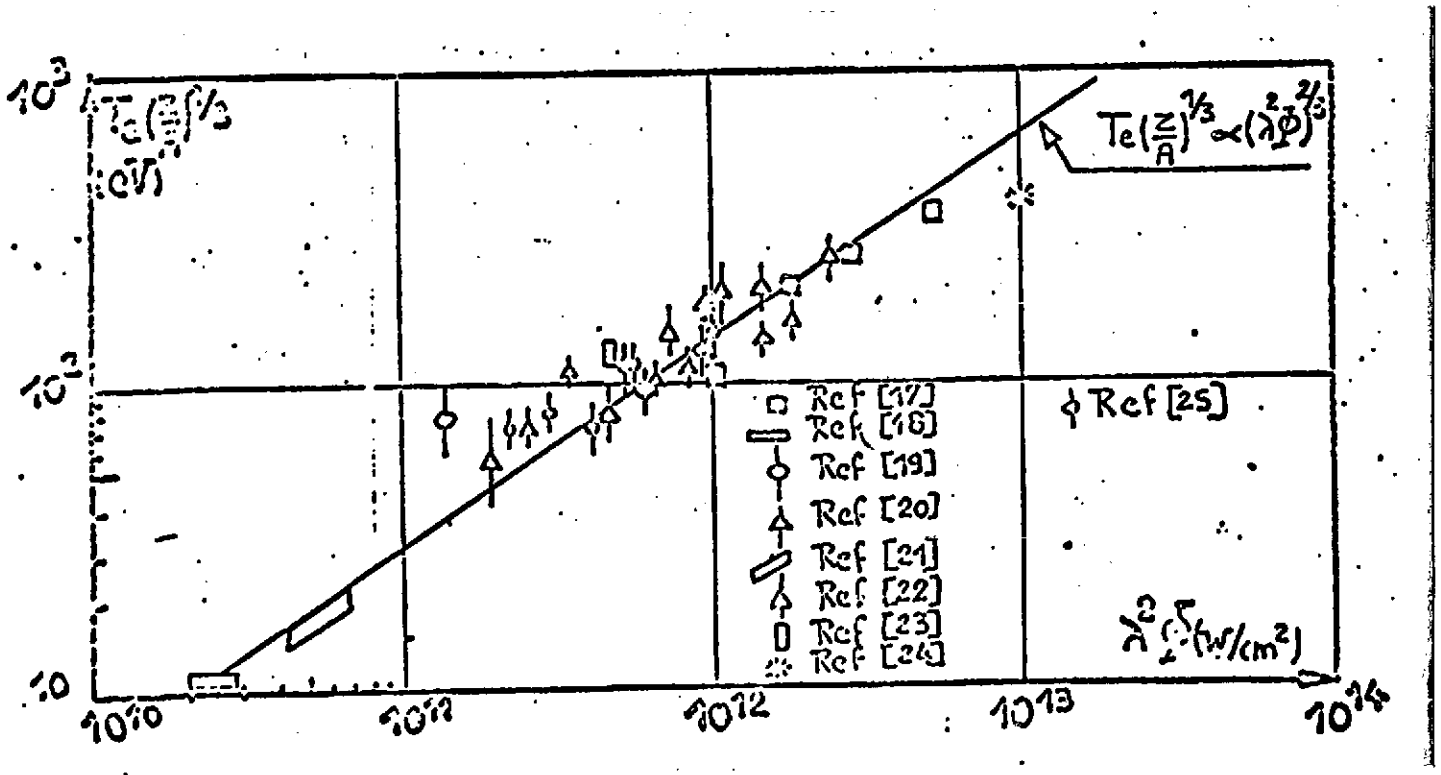


Fig. 1. a) Diagram of laser-matter interaction.
b) Density and temperature profiles during radioactive deflaglagration.
c) Development of speed over a period of time.

Fig. 2. Variation in the electronic temperature of the plasma as a function of the incident laser flux.



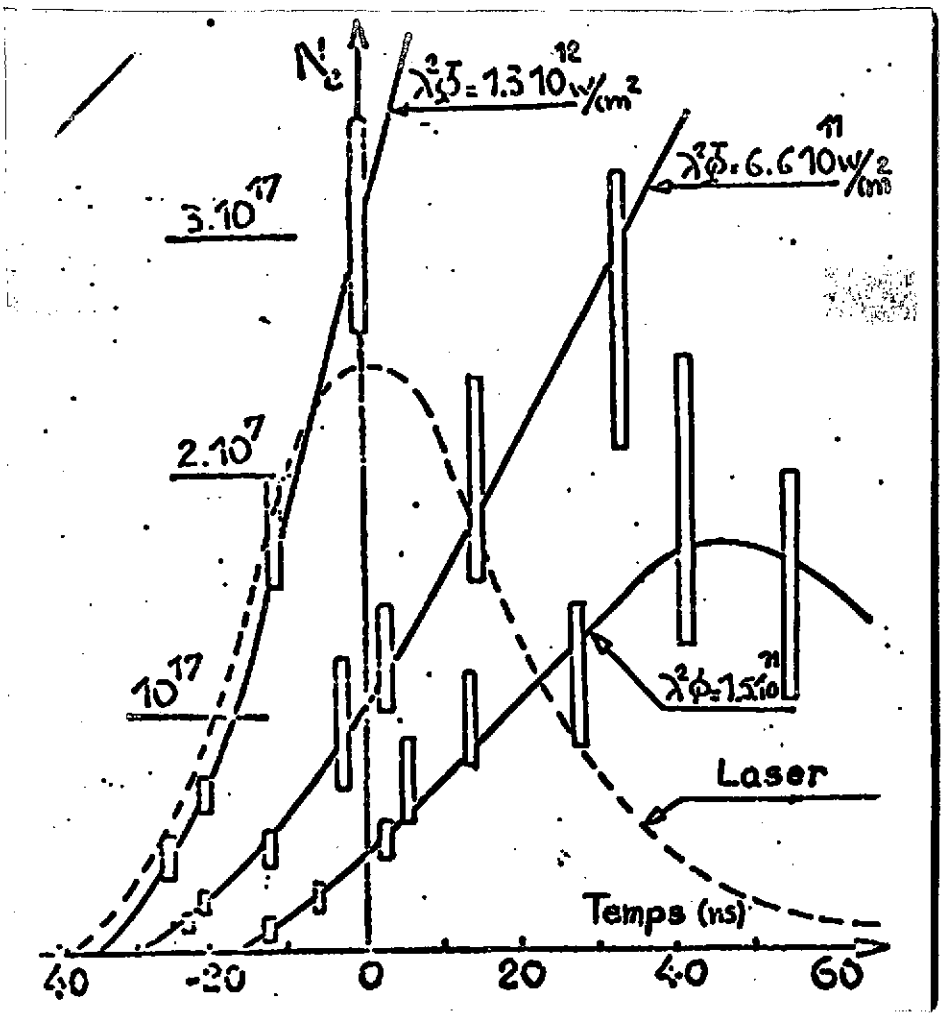


Fig. 3. Total number of electrons produced during the laser pulse (see G. Tonon et al.[26]).

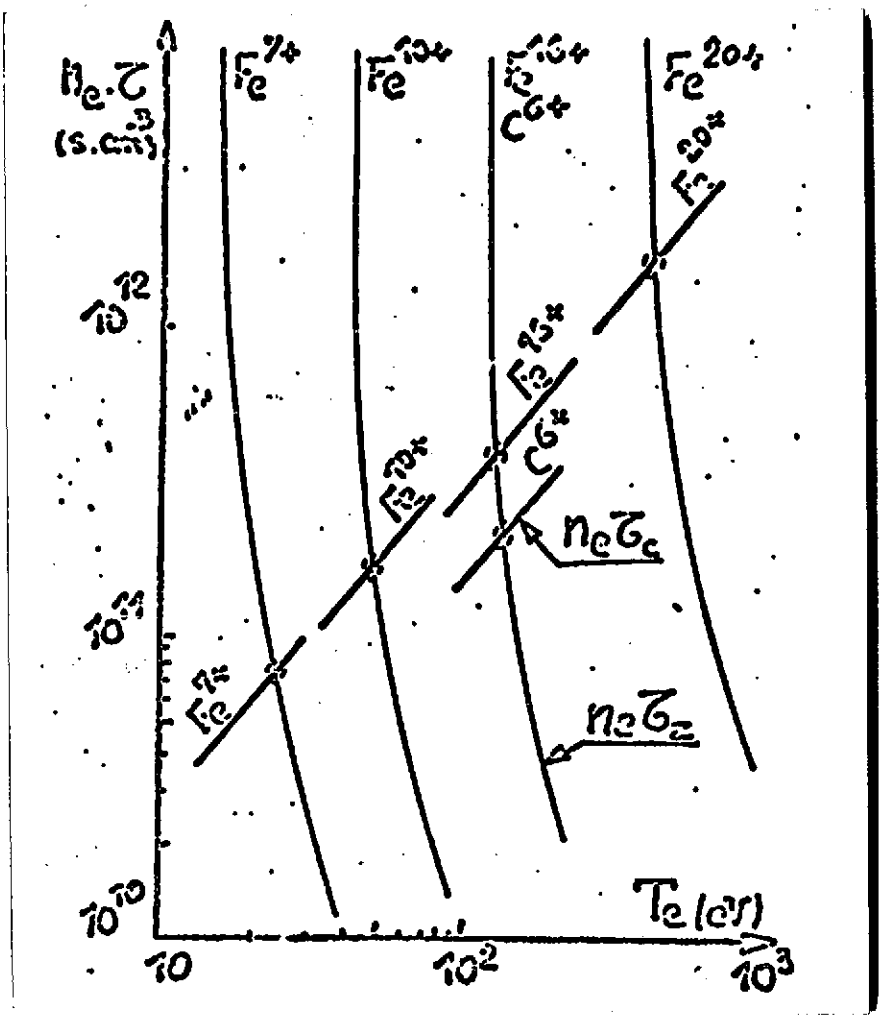


Fig. 4. Development of ionization time τ_Z and preheating time τ_c for carbon and iron ions.

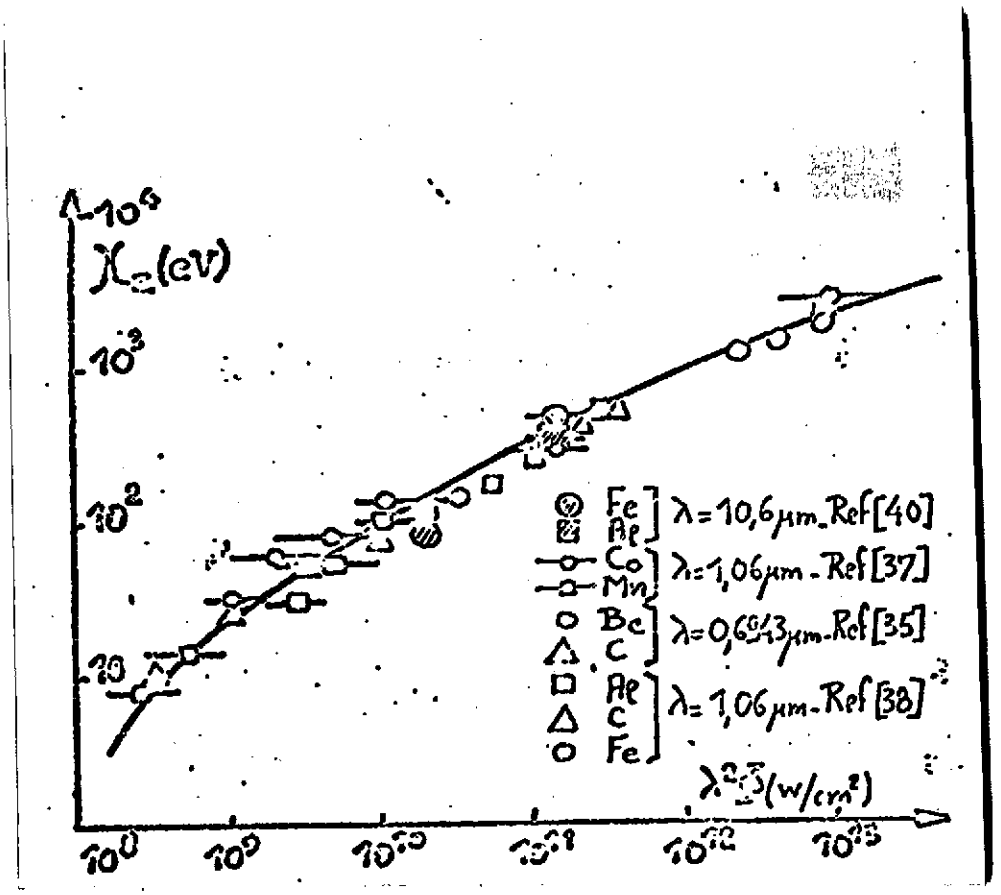


Fig. 5. Variation in ionization potential (relative to detected charge Z ions) as a function of incident laser flux.

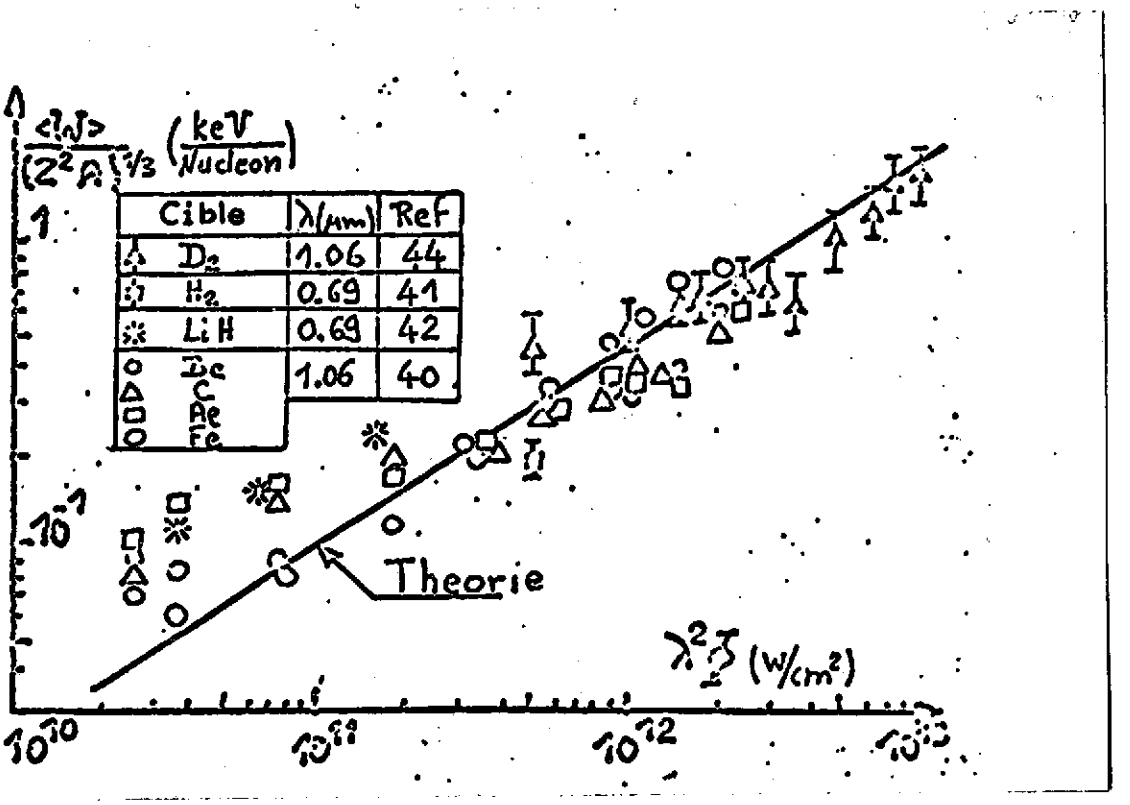


Fig. 6. Average kinetic energy of various types of ions as a function of laser flux.

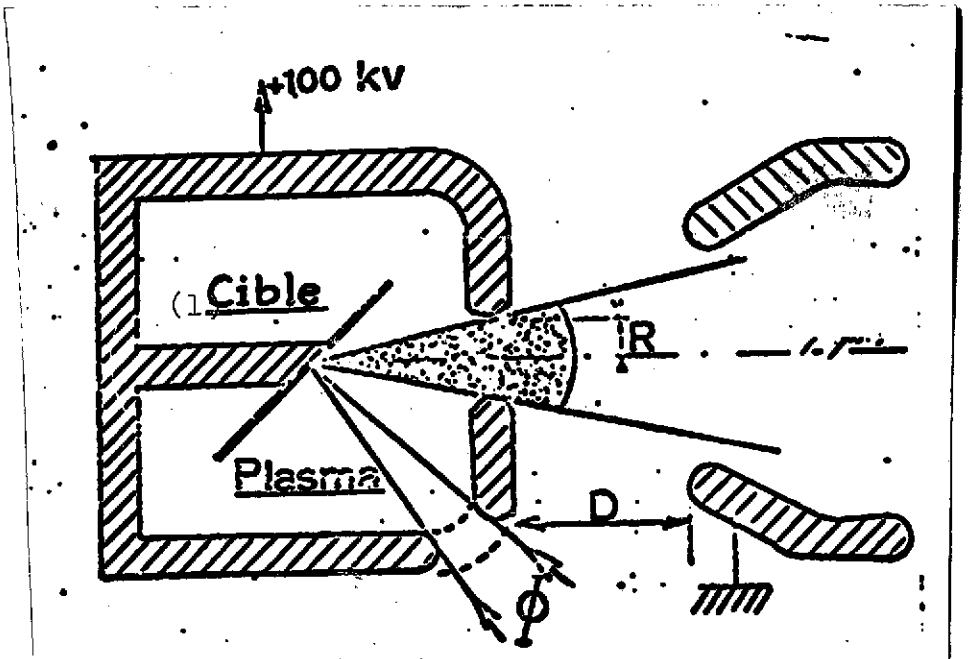


Fig. 7. Diagram of extraction in flight (see Ref. 46).

Key: 1. Target.